Spin-Density-Wave Band Gap in Chromium Thin Films

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INTRODUCTION

Magnetism and, especially, antiferromagnetism in thin films is a topic that has recently gained a lot of attention, the reason being twofold. For one, these magnetic layers can be arranged as multilayers that exhibit the giant magnetoresistance effect, such as in the ferromagnetic-antiferromagnetic FeCr multilayer system [1]. On the other hand, research into high transition temperature superconductors has revealed many material systems that exhibit antiferromagnetic phases [2], pointing towards a possible relationship between superconductivity and antiferromagnetic coupling. The analysis of such complex systems can be guided by the study of simpler materials, among which Cr metal has a special place in that it is not only an itinerant antiferromagnet, but also exhibits an incommensurate spin density wave (SDW), thus relating Fermi surface features to the magnetic properties [3]. Indication that the formation of the SDW below the Néel transition leads to a considerable reduction of the Fermi surface came originally from anomolous skin effect [4] and de Haas – van Alphen [5] measurements. A more direct determination of the electronic bandstructure from photoemission [6,7,8,9,10], however, encountered the problem of residual surface contaminants and was so far inconclusive, especially the formation of an energy gap or a transition temperature could not be established.

We have performed angle-resolved photoelectron spectroscopy (ARPES) experiments with high momentum and energy resolution on ultra-clean Cr(110) thin films that provide electronic bandstructure data. For the first time, direct evidence of the bandstructure backfolding as well as of the behaviour of the order parameter, i.e. the SDW energy gap that closes a function temperature, is presented.

EXPERIMENT

The ARPES experiments were carried out at beamline 7.0.1 at the Advanced Light Source. The energy resolution used was 50 meV, the momentum resolution was 0.05 ($2\pi/a$), with a = 2.88 Å, the lattice constant of Cr. The Cr(110) surface was prepared in ultra-high vacuum by evaporation of Cr onto a clean W(110) crystal and subsequent annealing. From a measurement of the size of the BZ, the film surface was strain-free. The crystal perfection of the Cr thin film was judged from a (1×1) LEED pattern as well as from the sharpness of the photoemission features.

EXTENT AND MAGNITUDE OF THE ENERGY GAP

From the previous experimental and theoretical work it is established that the nesting of the SDW wave vector, $\mathbf{q}_{SDW}$, with respect to the bcc Brillouin zone Fermi surface occurs between the electron "octahedron" at Γ and the hole "octahedra" at the six H points. These Fermi surface structures are of very similar shape and curvature, as sketched in Fig. 1a. We chose the photon energy so that $k_\perp$ samples the bulk BZ (on which the surface BZ is superimposed) at Γ. Experimental bandmaps with this $k_\perp$ and with $k_\parallel$ varied along Γ–S were taken at temperatures above (panel b, T = 490K) and below (panel c, T = 300 K) the measured surface Néel temperature (440 K, see below). In comparing comparing Fig 1b with Fig. 1c we observe (i) a second branch emerges at low temperature that is falling towards S, albeit weaker in intensity

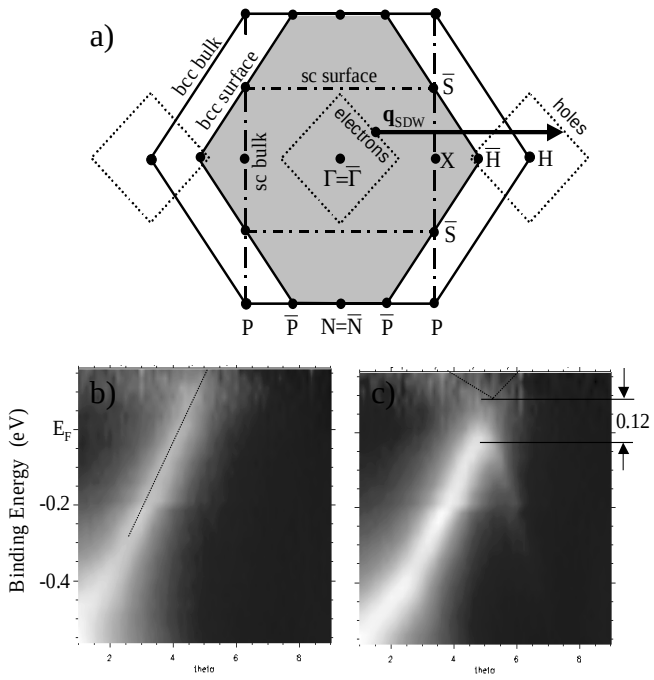

FIG. 1. a) Schematic of the bulk and superimposed surface BZ. Below bandmaps along Γ-S taken at b) +190 ºC and c) R.T. (Fermi distribution eliminated by division through background in a featureless region). In c) the upper branch can also be seen.

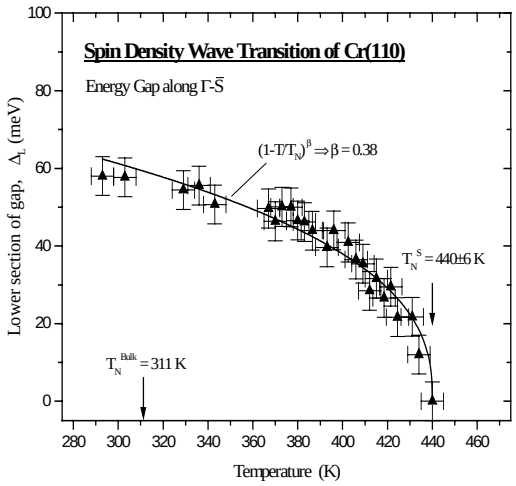

FIG. 2. Lower section of the SDW energy gap. The critical behaviour near the surface phase transition can be fitted with a power law.

than the branch rising from Γ, and (ii) a band forms above E_F that exhibits a minimum in close vicinity to the maximum of the band below E_F, thus forming an almost direct gap which we determine to 120 meV. We associate this gap with the formation of a static spin density wave. We find that the gap is reasonably well matched in position, though not energy, by first-principles calculations, and that it extends with approximately constant magnitude over much of the electron octahedron. Moreover, using wider scans, we infer a nesting vector of $\mathbf{q}_{SDW} = 0.95 \pm 0.02$ Γ–H, which is in excellent agreement with neutron scattering measurements [11].

CRITICAL BEHAVIOUR AT THE SURFACE PHASE TRANSITION

We monitored the order parameter of the phase transition by measuring the temperature-dependence of the energy gap. This implies acquisition of energy band maps like in Fig. 1 as a function of temperature and laying cuts at about 40% Γ–S in order to document the magnitude of the energy gap. From closer examination of numerous individual bandmaps, a surface transition temperature of $T_N^S = 440\pm10$ K is determined, considerably above the bulk Néel temperature of $T_N^B = 311$ K. The temperature dependence of the peak position of the lower branch is plotted in Fig. 2. The data can be represented quite well over a relatively wide temperature range by a power law $(1-T/T_N)^\beta$ with $\beta = 0.38 \pm 0.05$. For comparison, the 3D Ising exponent is 0.325 and the mean-field exponent is 0.5. Given the long spatial range of the spin wave, an exponent intermediate between these two is quite reasonable.

However, in looking at the critical behavior of the magnetization, determined as a bulk quantity from neutron scattering [3], it is generally inferred that the transition, contrary to expectation for

a simple spin system, is of "weak" first order, with a small discontinuity at the critical temperature T_N^{Bulk}. The data shown in Fig. 2 are compatible with a small discontinuity to the first or second data point below the transition. To our knowledge, however, no other truly surface-sensitive measurement of the surface transition exists. Moreover, no surface phonon dispersion or surface magnetic moment determination at the (110) surface has been carried out. From W(110) it is known that a surface phonon anomaly exists [12], indicative of significant electron-phonon coupling at the surface. If this were also true for the homologous d-transition metal chromium, then such enhanced coupling could also to lead to a weak first order transition.

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